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ORIGINAL PAPER

Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps

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Abstract The Southern Alps host volcano-sedimentary basins that formed during post-Variscan extension and strike-slip in the Early Permian. We present U–Pb ages and initial Hf isotopic compositions of magmatic zircons from silicic tuffs and pyroclastic flows within these basins, from caldera fillings and from shallow intrusions from a 250 km long E–W transect (Bozen–Lugano–Lago Maggiore) and compare these with previously published data. Basin formation and magmatism are closely related to each other and occurred during a short time span between 285 and 275 Ma. The silicic magmatism is coeval with mafic intrusions of the Ivrea-Verbano Zone and within Austroalpine units. We conclude that deep magma generation, hybridisation and upper crustal emplacement occurred contemporaneously along the entire transect of the Southern Alps. The heat advection in the lower crust by injected mantle melts was sufficient to produce crustal partial melts in lower crustal levels. The resulting granitoid melts intruded into the upper crust or rose to the surface forming large caldera complexes. The compilation of Sr and Nd isotopic data of these rocks demonstrates that the mantle mixing endmember in the melts may not be geochemically enriched but has a depleted composition, comparable to the Adriatic subcontinental mantle exhumed to form the Tethyan sea floor during Mesozoic continental breakup and seafloor spreading. Magmatism and clastic sedimentation in the intracontinental basins was interrupted at 275 Ma for some 10–15 million years, forming a Middle Permian unconformity. This unconformity may have originated during large-scale strike-slip tectonics and erosion that was associated with crustal thinning, upwelling and partial melting of mantle, and advection of melts and heat into the crust. The unconformity indeed corresponds in time to the transition from a Pangea-B plate reconstruction for the Early Permian to the Late Permian Pangea-A plate assembly (Muttoni et al. in Earth Planet Sci Lett 215:379–394, 2003). The magmatic activity would therefore indicate the onset of >2,000 km of strike-slip movement along a continental-scale mega-shear, as their model suggests.

Keywords Southern Alps · Permian basins · U–Pb age determinations · Zircon · Hf isotopes · Pangea reconstructions

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Introduction

A growing body of evidence suggests that melt extracted from the mantle and lower crust, melt ascent to higher levels and the final emplacement of magma in the upper crust occur at 10^3–10^5 years' time scales (e.g. Petford et al. 2000; Lowenstern et al. 2000). This contrasts with the classical ideas of long-lasting protracted magmatic and thermal events during an orogeny and instead asks for short-lived changes of the thermal structure of the crust. In particular, in crustal-scale extensional and/or strike slip tectonic settings, magma generation in the lower crust is triggered by the advection of liquids and heat from uplifted portions of the mantle. As a consequence, several magmatic processes may act almost contemporaneously at different crustal levels. These processes include partial melting of mantle rocks, segregation of melts and their ascent into the crust, contamination of melt by crustal material and emplacement of hybrid magmas in the upper crust or at the surface. The life time of such crustal scale magmatic systems could be as short as a few million years. Precise U–Pb age determinations are needed to test for postulated genetic links among magmatic rocks. We anticipate that high-resolution U–Pb age data from a series of co-magmatic rocks across Earth's crust may provide a sufficiently precise temporal framework to assess such relationships. Magmatic rocks suitable for this purpose could include the following: (1) lower to middle crustal gabbros to diorites, originating from partial melts in the underlying mantle; (2) granitoid rocks in the middle-to-upper crust and (3) shallow intrusive and volcanic rocks, such as flows and tuffs in extensional basins and caldera structures at the surface. The majority of these lithologies are expected to have a hybrid character, still recording the mantle heritage of parental magmas, but contaminated to different degrees by crustal materials. Unfortunately, coherent geological exposures exhibiting magmatic rocks on a truly crustal scale are rare.

This study focuses on one such exceptional setting in the Southern Alps (Northern Italy; Fig. 1), where magmatic rocks of supposed Early Permian age have solidified at different levels of the Earth's crust. It is our aim to establish a sound geochronological framework for the duration of the Early Permian magmatism in the Southern Alps on the basis of available and new U–Pb ages. This framework will serve as a test for the hypothesis of coeval crustal scale magmatism as previously proposed by several authors (see references below). In addition, Sr–Nd–Pb data of granitoid rocks from the literature in combination with new results of initial Hf isotopic ratios of dated zircons provide a time- and inheritance-resolved evaluation of the isotopic composition and origin of the melts. For these purposes we analysed U, Pb and Hf isotopes of zircons from magmatic rock samples of the Athesian Volcanic Group (Bolzano/Bozen), the Lugano-Valganna area,

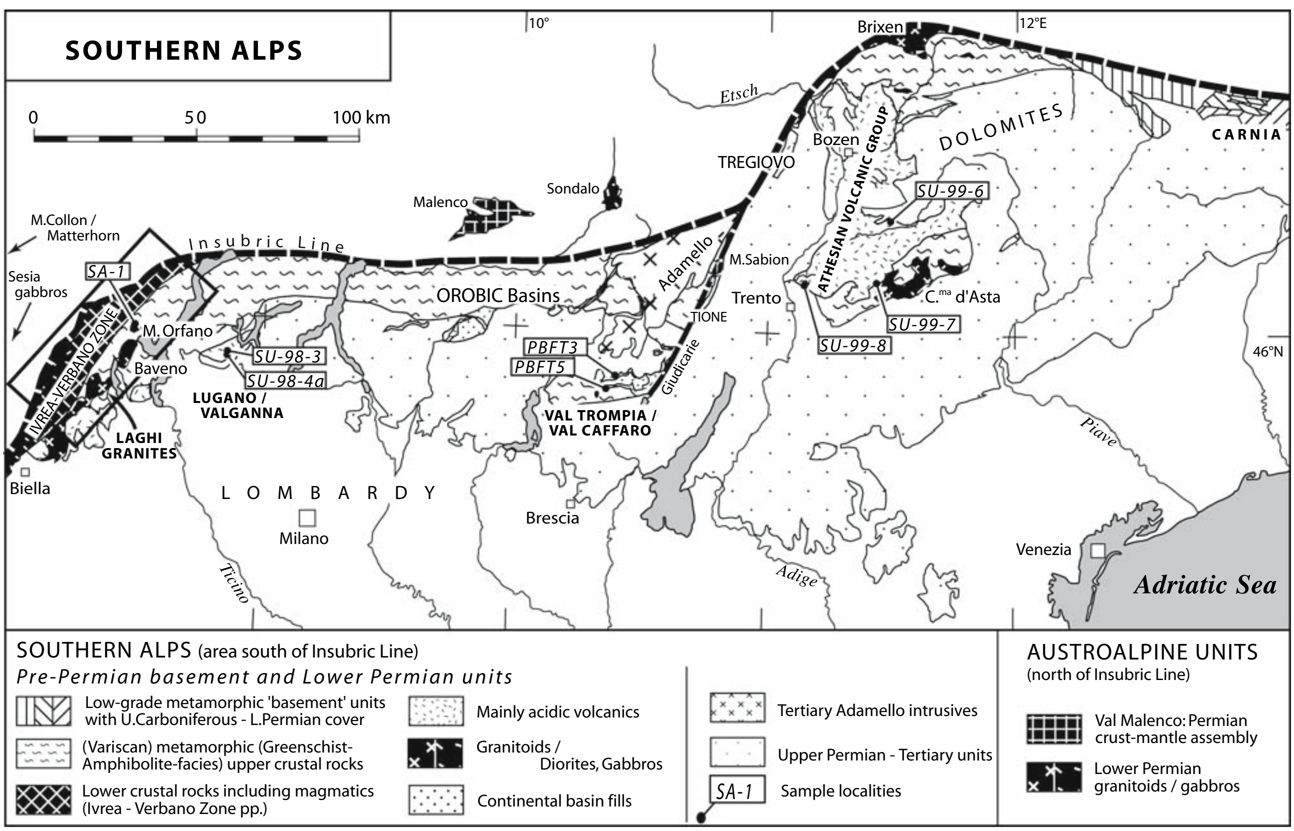

Fig. 1 Distribution of pre-Early Permian basement and cover rocks of the Southern Alps and location of samples taken for U–Pb age dating. The black frame approximately marks the crustal section displayed in Fig. 5. Also indicated are Austroalpine areas with dated Early Permian magmatic rocks (north of Insubric Line)

and the ‘‘Laghi Granites’’ in the central and western Southern Alps respectively (Fig. 1). Finally, the original spatial arrangement of the different magmatic bodies will be illustrated in a restored crustal transect of the Southern Alps for the Early Permian and its larger-scale geodynamic context will be briefly discussed.

The rocks of the Early Permian crust of the Southern Alps and Permian magmatic rocks in adjacent areas

Crystalline rocks of pre-late Permian age are exposed along up to 30 km wide band south of the Insubric Line and, with a sinistral offset by the Miocene Giudicarie Line, northeast of the Tertiary Adamello intrusion (Fig. 1). These units comprise a pre-Late Carboniferous basement, Early Permian intrusions and an Upper Carboniferous–Permian sedimentary and volcanic cover. The basement and cover rocks are deformed but show minimal evidence of an Alpine thermal overprint. With the Alpine shortening direction oriented roughly perpendicular to the strike of the South-Alpine fold belt, the array of pre-Mesozoic rocks displays largely the original post-Variscan configuration when adjusted for the E–W directed extension during the Mesozoic (e.g. Bertotti et al. 1993).

The pre-Permian basement

The pre-Permian basement between Biella and Carnia is affected by Variscan metamorphism increasing from greenschist-facies in the eastern/central to amphibolite-facies in the western part (e.g. Serie dei Laghi) of the Southern Alps. The non-to-weakly metamorphic basement rocks of Carnia in the eastern Southern Alps consist of deformed Ordovician to Lower Carboniferous volcanic and sedimentary successions; the central and western Southern Alps have Cambro-Ordovician to Silurian sediments (e.g. Kalvacheva et al. 1986; Gansser and Pantic 1988). Ordovician granitoids were deformed and metamorphosed during Ordovician and Variscan tectonism (Boriani et al. 1995; Zurbriggen et al. 1997). Variscan accretion is thought to have started in the Early Carboniferous (Läufer et al. 2001), and a metamorphic temperature peak was reached between 340 and 320 Ma. Late-orogenic cooling is recorded by Rb–Sr white mica and biotite cooling ages. Extrapolation of the cooling rates suggests that by 305 Ma, some of the currently exposed areas may have reached near-surface temperatures. Nonmetamorphic continental to littoral clastics resting unconformably on the metamorphic basement of the western and eastern Southern Alps indicate that penetrative deformation and metamorphism in the basement had ceased by Middle Westphalian/Late Moscovian times (Jongmans 1960).

A deeper part of this crust is exposed along the western border of the Southern Alps, in the Ivrea-Verbano Zone. This zone consists of slices of ultramafic rocks in contact with high grade metamorphic lithologies and mafic intrusions. Amphibolite to granulite facies metamorphism is thought to have outlasted the main period of Variscan deformation and metamorphism (e.g. Vavra and Schaltegger 1999; Vavra et al. 1999) but before the emplacement of the bulk of mafic magmas (Barboza and Bergantz 2000).

Lower Permian rocks

Lower Permian rocks range from marine carbonates, continental clastics and extrusive volcanics to plutonic rocks emplaced at all crustal levels.

In the easternmost Southern Alps (Carnia), distinct trough-like basins are filled with fluvio-deltaic to shallow marine, terrigenous and carbonate sediments of Late Carboniferous to Early Permian (Late Moscovian–latest Artinskian) age. These sediments unconformably cover deformed but only weakly metamorphosed pre-Moscovian volcano-sedimentary successions (Cassinis et al. 1997; Venturini and Spalletta 1998; Läufer et al. 2001) and are overlain by the Upper Permian redbeds of the Val Gardena sandstone. These along with equivalent redbeds (Verrucano Lombardo) also cover the metamorphic basement further to the west. In places, however, the basement rocks are overlain by up to 2 km thick continental sediments and volcanic rocks of Early Permian age. In the Etsch valley and in the area west of Lugano-Valganna volcanic rocks dominate, whereas near the Tertiary Adamello intrusion and in the Orobic Alps, the so-called Collio basins are largely filled by clastic sediments. In areas adjacent to the main volcanic districts the basement of the central and western Southern Alps also hosts numerous complexes of shallow crustal intrusions, up to 10–20 km wide and of Early Permian age (e.g. Brixen-Iffinger, Cima d’Asta, M. Sabion, Montorfano, Baveno, Alzo-Rocca Pietra).

The visible part of the deep Permian crust along the western border of the Southern Alps (Ivrea-Verbano Zone) is comprised of mafic intrusions (e.g. Rivalenti et al. 1984; Pin 1986; Voshage et al. 1990; Quick et al. 1994), which are at least in part, Early Permian in age. Early Permian mid-crustal and deep-seated gabbro intrusions are also preserved in several Austroalpine units to the north of the Insubric Line (e.g. Sondalo: Bachmann and Grauert 1981; Tribuzio et al. 1999; Malenco: Hansmann et al. 2001; Sesia-Lanzo: Bussy et al. 1998; Rebay and Spalla 2001; Mt. Collon-Dent Blanche: Monjoie 2004). These areas no longer display coherent crust-scale sections due to Alpine tectonism. However, because of their supposed pre-Jurassic proximity to the South Alpine realm (e.g. Brack et al. 1999), information from the westernmost Austroalpine units complements the reconstruction of the Permian South Alpine crust. In particular, a unique lithological crust-mantle boundary of Permian age is preserved in the Malenco ultramafic complex where mantle peridotites and granulite-facies crustal rocks are intruded by a Lower Permian gabbro (Hermann et al. 1997; Hansmann et al. 2001).

General age and setting of the Permian magmatic rocks

Geochronological data of Permian magmatic rocks in the Southern Alps mainly comprise Rb–Sr whole-rock and mineral ages. However, the Rb–Sr system is prone to post-crystallisation overprinting (e.g. Barth et al. 1993) and these ages must therefore be interpreted with caution. Indeed, during Mesozoic times, fluid-assisted thermal modification did affect parts of the South Alpine basement and resulted, e.g. in uranium deposits and widespread alteration of magmatic rocks (Cadel et al. 1987; Barth et al. 1992) as well as in the resetting of isotope systems of various minerals (Lu et al. 1997; Grieco et al. 2001).

Nevertheless, the majority of age results available for Early Permian magmatic rocks of the Southern Alps fall in the range 290–260 Ma, more than 15 m.y. younger than the latest phases of Variscan deformation. The formation of Permian basins and the associated magmatic products could have been caused by extension during post-orogenic crustal relaxation (Henk et al. 1997), or, alternatively, by large-scale strike-slip movements along the southern margin of the Variscan orogen (Handy and Zingg 1991; Handy et al. 1999). The occurrence of large volumes of intrusive rocks at the crust-mantle boundary clearly points to the involvement of the mantle in the melt forming process.

The Permian magmatic districts of the Southern Alps: available age data and location of the studied samples

Athesian Volcanic Group and related plutons

The Athesian Volcanic Group (AG) in the Etsch valley (Bolzano/Bozen) and its western periphery within the area of M. Luco-Tregiovo in southern Tyrol and Trentino (Fig. 1) extends over more than 2,000 km^2 and consists of up to >2 km thick suites of calc–alkaline volcanic and subvolcanic rocks, including basaltic andesites, andesites, dacites, rhyodacites and rhyolites (see detailed description and further references in Bargossi et al. 1998). The magmatic rocks comprise of domes and lava flows, pyroclastic and surge deposits and ignimbrites. The volcanic successions unconformably overlie pre-Permian basement with a local and thin clastic cover (Waidbruck/Ponte Gardena Conglomerate). Continental sediments of reduced vertical and lateral extent also occur at different stratigraphic levels inside the AG. A possible tectonic control on the location and distribution of the AG magmatics is as yet uncertain and at least some of the major volcanic units of the AG could represent large caldera infills above shallow crustal magma chambers. The adjacent pre-Permian basement north and south of the AG is indeed penetrated by granitoid plutons (Brixen-Iffinger-M. Croce, Cima d'Asta) and smaller satellite intrusions, including more mafic plutonic rocks. Geometrical relationships (vicinity of plutonic and volcanic rocks) suggest that these magmatic bodies were emplaced within the uppermost 10 km of the Early Permian crust. Similar intrusions may occur also underneath the AG and the effective volume occupied by plutonic rocks must greatly exceed that of the visible parts. The same may also be true for the volcanic rocks, portions of which are hidden beneath the Mesozoic cover.

For a graphic compilation and discussion of the numerous available radiometric age data of magmatic products of the AG and related granitoids, we refer to Barth et al. (1994) and Bargossi et al. (1998). According to the data of Barth et al. (1994) magmatic activity seems to have peaked around 276 Ma; preliminary U–Pb zircon ages of Klötzli et al. (2003) (see also Marocchi et al. 2005) constrain the main period of volcanism of the AG to the time span between 285 and 274 Ma with local basaltic andesites at the base of the volcanic suite being possibly somewhat older (Visonà et al. 2005). The upper age limit for the AG magmatism includes the youngest preserved volcanic member (Ora Fm. of Marocchi et al. 2005 = Predonico Ignimbrite of earlier studies), which lies on top of the clastic Tregiovo Formation. The latter has yielded a Kungurian or slightly younger stratigraphic age, based on palynomorphs (Neri et al. 1999).

Sample locations

In order to further explore the time span of magmatic activity of the AG, we collected material from the southern portion of the AG, i.e. in the area to the northeast of Trento (Fig. 1). In the gently NW-dipping hangingwall of the Tertiary Valsugana thrust, the pre-Permian basement is cut by the shallow intrusions of Cima d'Asta including a granodiorite with a Th–Pb allanite age of 275.5 ± 1.5 Ma (Barth et al. 1994). The top of the basement is overlain by a >1.5 km thick volcanic succession. From this impressive pile of extrusive rocks we analysed a sample from its deeper (though not the lowermost) portion and two samples from the uppermost parts of the volcanic sequence. The ''stratigraphically'' deepest specimen (sample SU-99-7) is from the ''Lower Rhyodacitic Ignimbrites'' (Bargossi et al. 1993a, 1998) and was collected along the main road in Val Calamento, at an altitude of 1,320 m and 100 m southeast of Malga Baessa. Two samples from the area of Val di Cembra–Val di Fiemme are from the youngest preserved volcanics at roughly equivalent levels of the ''Upper Rhyolitic Ignimbrites'' (Bargossi et al. 1998) and immediately below the capping Upper Permian redbeds (Val Gardena Sandstone). Sample SU-99-8 is a red- to brown-coloured ignimbritic rhyolite from the uppermost quarry along the road approximately 1 km north of the S. Colomba lake (area of Albiano; for a recent geological map see Selli et al. 1996). Such rocks are typical for those exploited in numerous quarries in the lower Val di Cembra and are widely used for construction purposes and pavements all over western Europe. Sample SU-99-6 was taken 500 m east–southeast of the village San Lugano, at the base of a cliff east and above the main road between Auer and Cavalese. The voluminous ''Upper Rhyolitic Ignimbrites'' are thought to extend to the northern areas of the AG, where Barth et al. (1994) obtained a Th–Pb allanite age of 276.3 ± 2.2 Ma for its vitrophyric basal facies. Moreover, this unit is possibly equivalent with the volcanic products of the Ora Fm. whose age ranges between 277.0 ± 2 and 274.1 ± 2 Ma near Tregiovo and S. Giacomo (Marocchi et al. 2005) and which may, at least in part, represent the fill of a huge caldera.

Collio-type basins (Orobic basins; Val Trompia-Val Caffaro basin)

In contrast to AG, the infill of the Collio-type basins of the Brescian and Bergamasc Alps comprise thick piles of clastic sediments (e.g. Cassinis et al. 1988). The asymmetric Orobic basins in the Bergamasc Alps (Cadel et al. 1987, 1996; Sciunnach 2001a, b) consist of a lower volcanic member and an upper sedimentary member. From the lower rhyolitic group Cadel et al. (1987) and Philippe et al. (1987) report U–Pb zircon age values of 288.4 and 280 ± 3 Ma. The Collio basin of Val Trompia–Val Caffaro is considered as a fault-bounded pull-apart structure which originated within a large-scale dextral transfer system (Cassinis et al. 1997). This pronouncedly asymmetric basin contains two distinct intervals of mainly ignimbritic volcanic rocks, which bracket the up to 1,500 m of clastic fill. Minor bodies of shallow intrusives and domes at the periphery and in the immediate vicinity of the basin are potential sources for the basinal volcanic deposits (Breitkreuz et al. 2001). Schaltegger and Brack (1999) and Brack and Schaltegger (1999) quoted preliminary U–Pb zircon ages of around 283–280 Ma for the volcanic layers at the base (Sample PBFT5) and on top of the clastic basin fill (Sample PBFT3), indicating a time span of 3.3 ± 1.6 m.y. for the formation of the preserved portion of the Val Trompia–Val Caffaro basin. This case study will be described in a forthcoming paper (Brack and Schaltegger, in preparation). Rb–Sr biotite ages (274–271 ± 4 Ma; De Capitani et al. 1994) of nearby granitoid plutonic rocks (Navazze, Val Trompia) are broadly in agreement with the age of the volcanic rocks. The volcanic-dominated successions of the Tione basin in Val Rendena (Bargossi et al. 1993b; Cortesogno et al. 1998) with the adjacent Permian intrusion of M. Sabion show similarities with and may originally have been in continuity with the north-eastern portion of the Collio basin of Val Trompia–Val Caffaro.

The magmatic district of the Laghi area (Lugano-Valganna, the ''Laghi Granites'', the Ivrea-Verbano Zone)

Another center of Early Permian magmatism is situated in the areas to the east and southwest of Lago Maggiore and includes the deep crustal mafic magmatism of the Ivrea-Verbano Zone (Fig. 1). Felsic volcanic rocks are preserved along the Southern Alps border northeast of Biella. To the east of Lago Maggiore, prominent volcanic successions occur between Lugano and Valganna (Buletti 1985). Before and during Permian times, and before being separated by an originally E-dipping (Early Jurassic) Lago Maggiore normal fault (Bertotti 1991; Bertotti et al. 1993), the Lugano-Valganna extrusive complex and the pluton-bearing basement west of Lago Maggiore were possibly positioned in closer proximity than today.

Lugano-Valganna

The Lugano-Valganna complex is composed of approximately 1,800 m of mainly extrusive volcanic rocks, intruded by the subvolcanic, pink-coloured ''Ganna granite'' stock, which most likely represents the latest magmatic event in the region. On the basis of intrusive contacts, Bakos et al. (1990) considered this assembly as the result of the foundering of a caldera. The intra-caldera succession consists of a series of tuffs, ignimbrites and lavas including andesitic to dacitic flows and thin intercalations of clastic rocks. The age of the Lugano-Valganna complex remains controversial. Stille and Buletti (1987) interpreted different whole-rock and mineral isochron ages of 340 Ma as mixing lines due to crustal contamination and postulate an emplacement age of 262 ± 1 Ma on the basis of a Rb–Sr mineral isochron obtained on a dacite south of Lugano. However, this age is significantly younger than whole-rock and mineral Rb–Sr isochron age values of 275 ± 8 and 281 ± 9 Ma for the Ganna granite (Bakos et al. 1990).

In order to establish the maximum age as well as the time of peak magmatic activity, two samples of magmatic rocks were collected in Valganna. Sample SU-98-4a is from the oldest tuffs (''Lower ignimbritic tuffaceous series'' of Bakos et al. 1990) overlying the pre-Permian basement along the road from Ganna to Boarezzo. Sample SU-98-3 is from the intrusive subvolcanic granite in an abandoned quarry around 250 m northwest of the village of Boarezzo.

''Laghi Granites''

To the west of Lago Maggiore and south of Val d'Ossola the pre-Permian basement rocks of the ''Serie dei Laghi'' host numerous small to medium-sized granitic plutons (e.g. Montorfano, Baveno-Mottarone, Alzo-Roccapietra). These bodies show little deformation and belong together with their host rocks to a southeast-dipping tilted segment of upper crust. A high-temperature fault zone of Permian age known as the Cossato–Mergozzo–Brissago (CMB) fault separates this portion of upper crust from the deep crustal rocks of the Ivrea-Verbano Zone. Along the CMB-line numerous small hornblende-rich mafic-intermediate intrusions (''appinites'') occur (Boriani et al. 1990). The best estimates for the age of emplacement of members of the ''Laghi Granites'' are provided by Rb–Sr whole-rock ages of 277 ± 8 and 276 ± 7 Ma (Pinarelli et al. 1988) for Montorfano and for the Baveno granite, respectively. These values also conform with the 276 ± 5 Ma Rb–Sr whole-rock age obtained on samples from different plutonic bodies (Hunziker and Zingg 1980) but they are younger than the 295 ± 5 Ma U–Pb age of monazite from Montorfano (Köppel 1974).

In order to further evaluate the age of the ''Laghi Granites'' we analysed zircons from a medium-grained white biotite granite collected in the big quarry on the south-eastern flank of Montorfano (Sample SA-1). Whole-rock Nd and Hf isotopic data from this sample are reported in Stille and Steiger (1991).

Ivrea-Verbano Zone

Amphibolite to granulite facies metapelitic rocks, slices of peridotite and voluminous mafic intrusions are the main constituents of the Ivrea-Verbano Zone. To the northeast this zone is tectonically bound by the Alpine Insubric fault whereas a complex fault zone consisting of the Alpine Cremosina Line and the Early Permian high-temperature Cossato–Mergozzo–Brissago (CMB) Line separates the Ivrea-Verbano Zone from the upper crustal rocks of the ''Serie dei Laghi''. Northeast of Val d'Ossola the CMB Line is offset by the Pogallo Line (e.g. Boriani et al. 1990) of presumably early Mesozoic age (Hodges and Fountain 1984; Schmid et al. 1987; Handy 1987; Mulch et al. 2002; but for an alternative view see e.g. Boriani and Villa 1997). Metamorphic pressure estimates from metasediments and metabasic rocks (Schmid and Wood 1976; Henk et al. 1997; Demarchi et al. 1998; Handy et al. 1999) suggest that the Ivrea-Verbano Zone is a tilted (Mehnert 1975; Fountain 1976) and partly attenuated slice of lower crust (Zingg 1990; Zingg et al. 1990; Handy and Zingg 1991).

A large volume of mafic intrusives known as the ''Mafic Formation'' dominates the southwestern Ivrea-Verbano Zone and comprises a variety of partly layered gabbros, ultramafic rocks, and diorites (Rivalenti et al. 1984; Sinigoi et al. 1994; Quick et al. 2003). A U–Pb zircon age of 285 +7/–5 Ma for a diorite (Pin 1986) and SHRIMP U–Pb-ages of 285–287 Ma for the same and other lithologies of the ''Mafic Formation'' (Quick et al. 2003) suggest an Early Permian age for the emplacement of diorite magmas in the originally, structurally highest levels in the eastern part of the ''Mafic Formation''. Mingling of diorite and more mafic magma (e.g. Quick et al. 2003) probably related to the emplacement of large gabbro units in Val Sesia (Sinigoi et al. 1994) indicate that the different pulses are co-magmatic and we suggest that these values may represent an upper age limit for a large portion of the ''Mafic Formation''.

Analytical techniques

U–Pb age determinations

Zircons were air-abraded and washed in diluted HNO_3, distilled acetone and water in an ultrasonic bath. Dissolution in $HF–HNO_3$ using miniaturised dissolution vessels was followed by chemical separation on anion exchange resin using minimal amounts of ultra-pure acids. Isotopic analyses was performed at ETH Zürich in the years 1999–2001 on a MAT262 thermal ionisation mass spectrometer equipped with an ion counting system. The latter was calibrated by repeated analysis of the NBS 982 standard solution. Total procedural Pb blank was estimated at 1.5 ± 0.75 pg Pb and <0.1 pg U. A mixed ^{205}Pb–^{235}U tracer solution was used for all analyses. Common lead in excess of this amount was corrected with the model of Stacey and Kramers (1975). The uncertainties of the isotopic composition of spike, blank and common lead were taken into account and propagated into the final isotopic ratios. The ellipses in Fig. 2 represent 2σ uncertainties. Calculation of concordant ages and averages used the program of Ludwig (2000); errors on intercept ages and average concordant ages are given at the 95% confidence level.

Hf isotopes

The Hf fraction was isolated using Eichrom™ Ln-spec resin, and measured in static mode on a NuPlasma™ multi-collector ICP-MS using a MCN-6000 nebuliser for sample introduction. ^{176}Lu/^{177}Hf ratios of analysed zircons were not determined but ^{176}Lu/^{177}Hf ratios were corrected for a typical value of ^{176}Lu/^{177}Hf in zircon of 0.005; the correction stayed within limits of analytical precision of the measured ^{176}Hf/^{177}Hf ratios in all cases. The Hf isotopic ratios were corrected for mass fractionation using a ^{179}Hf/^{177}Hf value of 0.7325 and normalised to ^{176}Hf/^{177}Hf of 0.282160 of the JMC-475 standard (Blichert-Toft et al. 1997). Errors of the mea-

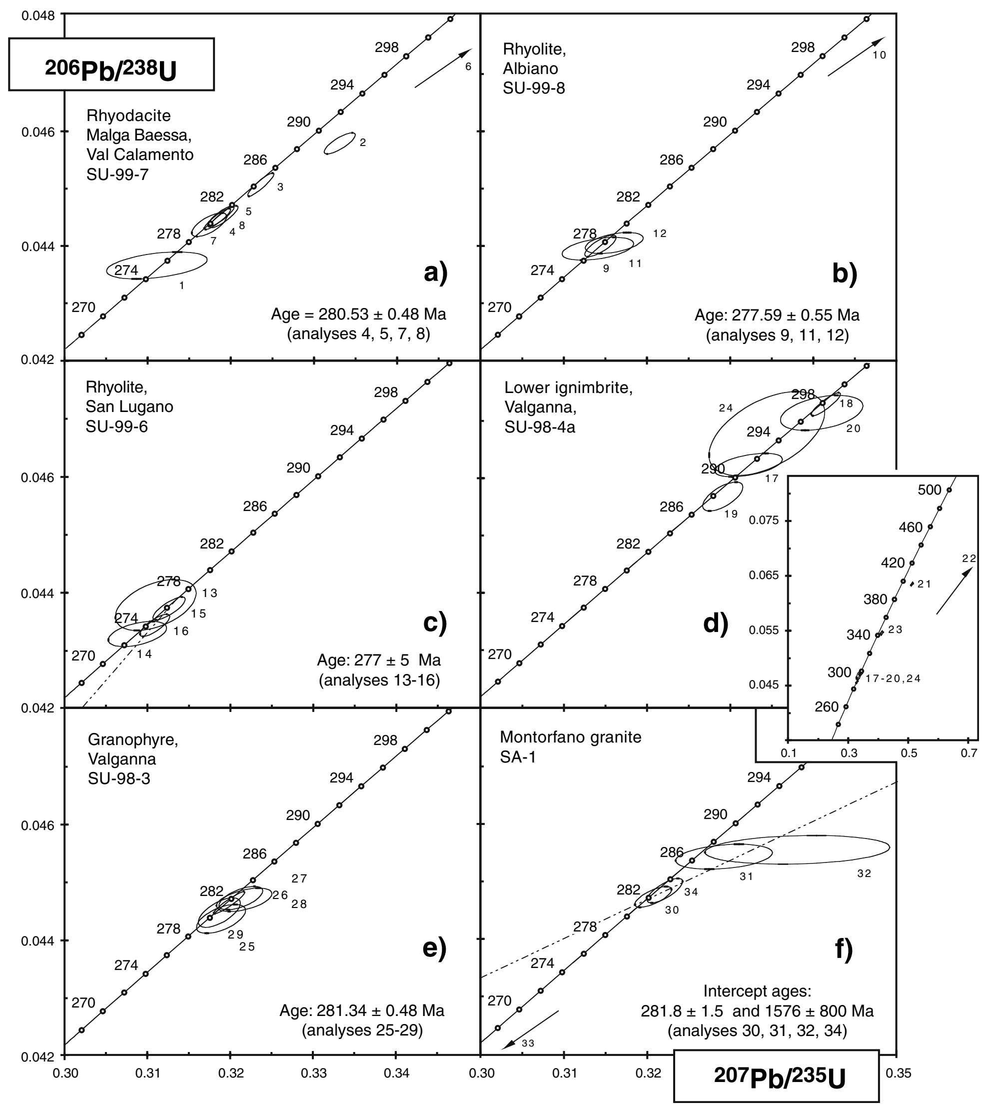

Fig. 2 U–Pb concordia diagrams of the dated zircons. **a** Rhyodacite from Val Calamento; **b** Ignimbritic rhyolite from Albiano-S.Colomba; **c** Rhyolite from San Lugano, all Athesian Volcanic Group; **d** Lower ignimbrite; **e** intrusive Ganna granite; **f** Montorfano granite

sured $^{176}Hf/^{177}Hf$ ratios are either given as external 2σ reproducibility of standard measurements (i.e. ±0.5 ε units) or individual 2σ errors, whichever is larger. εHf values and T_{DM} model ages were calculated with $(^{176}Hf/^{177}Hf)_{CHUR(0)} = 0.282772$ (Blichert-Toft and Albarède 1997) and use present-day depleted mantle values of $^{176}Hf/^{177}Hf = 0.283252$, $^{176}Lu/^{177}Hf = 0.04145$ and a crustal $^{176}Lu/^{177}Hf = 0.017$ (Blichert-Toft and Albarède 1997). Mean ages and mean Hf isotopic values are given at the 95% confidence level (Table 1).

U–Pb and Hf isotopic results and discussion of age data

Athesian Volcanic Group

Rhyodacite SU-99-7 (Malga Baessa, Val Calamento; Fig. 2a)

This sample contained a mixed zircon population. Twelve anhedral and colourless fragments of very-low-U zircons (12 ppm U) represented a suspicious sub-population and were analysed together (analysis 1). The result was an analytically concordant age of 275 Ma which is 5 m.y. younger than the other concordant zircons (albeit with a larger error than the other analyses) and can not be interpreted at present. Four analyses (4, 5, 7 and 8) consisting of 1–5 zircons each and with U concentrations between 200 and 500 ppm are perfectly concordant and define a concordant age of 280.5 ± 0.5 Ma. Analyses 2, 3 and 6 contain inherited components with $^{207}Pb/^{206}Pb$ ages of ca. 300 and 850 Ma. Four zircon fractions analysed for initial Hf isotopes (4–7) yielded a mean εHf of –5.4 ± 0.9 (Table 2). The strongly discordant analysis 6 did not show any difference in Hf isotopic composition, whereas the concordant analysis 7 is slightly lower. We thus assume that the scatter reflects a combination of natural and analytical variation.

Ignimbritic rhyolite SU-99-8 (Albiano, Val di Cembra; Fig. 2b)

Analyses 9, 11 and 12 consisting of one or two prismatic zircons resulted in a cluster of three concordant points with a mean age of 277.6 ± 0.6 Ma. Analysis 10 consisting of four grains contained an inherited component pointing to a $^{207}Pb/^{206}Pb$ age of 500 Ma. The zircon grains are rather low in U (120–220 ppm). Two concordant zircon fractions yielded an εHf of –2.7 (±0.5). Analysis 10 with evident inheritance yields a value of –6.8 substantiating the presence of an old crustal component in these zircons.

Ignimbritic rhyolite SU-99-6 (San Lugano, Val di Fiemme; Fig. 2c)

Four zircon fractions consisting of 3–7 grains each were analysed; the zircons are rather low in U (160–220 ppm) and yielded four analytically concordant points with $^{206}Pb/^{238}U$ ages scattering between 273.2 and 276.3 Ma. The rock showed relatively strong alteration and the data points are thus interpreted in terms of lead loss; a best fit line passing through the origin intersects the concordia at 277 ± 5 Ma, in perfect agreement with the more precise result on sample SU-99-8 in a comparable stratigraphic position. The initial Hafnium isotopic ratios of four zircon fractions yield a mean εHf value of 0.6 ± 0.6, which is distinctly higher than the value of the coeval rhyolite SU-99-8 at Albiano.

Discussion

The precise ages of samples SU-99-7 and SU-99-8 from the southern margin of the Athesian Volcanic Group record magmatic activity during 2.9 ± 1.1 million years (280.5 ± 0.5–277.6 ± 0.6 Ma), which resulted in a volcanic succession approximately 2,000 m thick. However, the older age does not date the earliest magmatic activity in the area because west of Val Calamento this interval is preceded by older volcanic rocks that overlie the pre-Permian basement and thin conglomeratic intercalations. Hence, the onset of AG magmatism may be closer to the ages around 284–285 Ma indicated by Klötzli et al. (2003) for volcanic rocks associated with the basal Waidbruck Conglomerates. Preliminary and less precise SHRIMP U–Pb data may point to an even older age for basaltic andesites in the northernmost part of the AG (Visonà et al. 2005). The 277.6 ± 0.6 Ma zircon age (sample SU-99-8) of the youngest preserved volcanic rocks of the ‘‘Upper Rhyolitic Ignimbrites’’ in the southern AG is in good agreement with the Th–Pb allanite age of 276.3 ± 2.2 Ma (Barth et al. 1994) at a presumably equivalent level (basal ‘‘Upper Rhyolitic Ignimbrites’’) in the northern AG. Klötzli et al. (2003) and Marocchi et al. (2005) suggest a somewhat younger age of 274.1 ± 2.4 Ma for the uppermost rhyolitic ignimbrite of the volcanic Ora Formation on top of the Tregiovo sediments along the western border of the AG. In spite of the remaining uncertainties with respect to the oldest and youngest preserved volcanic products, a time span of ≤10 m.y., i.e. between ca. 285 and

Table 1 U–Pb determinations of zircons from Permian igneous rocks of the Southern Alps

Number	Description[a]	Weight (mg)	No of grains	Concentrations				Atomic ratios							Apparent ages			Error corr.
				U	Pb rad. (ppm)	Pb nonrad. (pg)[b]	Th/U nonrad. (pg)[b]	206/204[c]	206/238[d]	Error 2σ (%)	207/235[d]	Error 2σ (%)	207/206[d]	Error 2σ (%)	206/238	207/235	207/206	
Rhyodacite, Malga Baessa, Val Calamento (SU-99-7)																		
1	Clrls frags	0.0215	12	19	0.86	2.9	0.49	403	0.04366	0.44	0.3111	1.59	0.05167	1.46	275.5	275.0	270.9	0.42
2	Prism to spr	0.0052	5	350	16.72	1.8	0.49	2949	0.04579	0.33	0.3331	0.46	0.05277	0.28	288.6	292.0	318.9	0.80
3	Prism incl	0.0090	3	579	24.76	2.6	0.35	5524	0.04507	0.37	0.3236	0.40	0.05209	0.17	284.2	284.7	288.5	0.91
4	Ipr incl	0.0237	2	221	10.38	4.5	0.53	3277	0.04447	0.34	0.3184	0.41	0.05193	0.18	280.5	280.7	282.5	0.90
5	Prism incl	0.0103	4	565	25.28	3.9	0.36	4259	0.04452	0.33	0.3188	0.41	0.05194	0.20	280.8	281.0	282.7	0.87
6	Prism to lpr	0.0110	2	192	9.86	1.3	0.14	1593	0.05019	0.34	0.4666	0.49	0.06743	0.31	315.7	388.9	851.0	0.80
7	Ige tips prism	0.0040	1	510	22.95	3.9	0.39	1495	0.04437	0.38	0.3174	0.54	0.05188	0.39	279.9	279.9	280.0	0.69
8	Prism	0.0051	5	368	16.68	1.1	0.41	4968	0.04451	0.35	0.3192	0.43	0.05201	0.21	280.8	281.3	285.8	0.87
Rhyolite, Albiano (SU-99-8)																		
9	Ipr P-type	0.0110	2	176	8.05	2.1	0.48	2558	0.04400	0.35	0.3144	0.49	0.05183	0.31	277.6	277.6	277.8	0.78
10	Prism small	0.0068	4	218	12.78	2.5	0.56	2098	0.05408	0.35	0.4263	0.49	0.05717	0.30	339.5	360.6	498.2	0.75
11	Tip of lge prism	0.0083	1	116	5.35	8.0	0.51	355	0.04395	0.37	0.3141	1.12	0.05183	1.01	277.3	277.4	278.1	0.45
12	Tip of lge prism	0.0264	2	227	10.32	39.9	0.46	437	0.04405	0.34	0.3161	0.90	0.05204	0.80	277.9	278.6	287.0	0.47
Ignimbritic rhyolite, San Lugano (SU-99-6)																		
13	Frags of lpr	0.0023	4	217	10.39	1.6	0.71	885	0.04379	0.82	0.3110	1.28	0.05151	1.16	276.3	274.9	263.7	0.46
14	Ipr	0.0055	3	162	7.66	4.4	0.66	582	0.04329	0.41	0.3088	0.93	0.05173	0.82	273.2	273.3	273.7	0.47
15	lpr to prism	0.0105	4	188	8.98	2.5	0.67	2206	0.04373	0.37	0.3126	0.51	0.05184	0.31	275.9	276.2	278.2	0.80
16	Frags	0.0067	7	170	8.10	1.0	0.69	3050	0.04344	0.36	0.3109	0.47	0.05191	0.29	274.1	274.9	281.3	0.79
Lower ignimbrite, Valganna (SU-98-4a)																		
17	lpr P-type	0.0022	6	190	9.48	1.6	0.63	508	0.04623	0.36	0.3322	1.00	0.05212	0.88	291.3	291.2	290.6	0.49
18	Prism	0.0070	1	412	19.03	2.2	0.26	1995	0.04729	0.35	0.3415	0.42	0.05237	0.19	297.9	298.4	301.7	0.89
19	Large brown prism	0.0044	1	215	10.47	1.4	0.57	1985	0.04568	0.45	0.3291	0.60	0.05225	0.46	288.0	288.9	296.4	0.65
20	Ipr P-type	0.0021	5	264	13.60	4.4	0.67	399	0.04714	0.53	0.3410	1.19	0.05247	1.09	296.9	297.9	305.9	0.40
21	Frags of pr	0.0035	8	300	18.87	4.8	0.27	907	0.06346	0.37	0.5124	0.57	0.05856	0.41	396.6	420.1	550.8	0.70
22	Brownish tips	0.0049	3	390	31.53	3.4	0.12	2726	0.07625	0.33	1.0397	0.39	0.09889	0.16	473.7	723.8	1603.4	0.91
23	Ipr to ac, P-type	0.0021	3	257	15.67	2.1	0.74	935	0.05459	0.47	0.4119	0.85	0.05472	0.73	342.6	350.2	400.9	0.51
24	lpr to ac, P-type	0.0015	5	283	13.84	2.3	0.53	555	0.04678	1.28	0.3344	1.70	0.05185	1.52	294.7	292.9	278.7	0.51
Granite, Valganna (SU-98-3)																		
25	lpr P-type	0.0029	5	506	23.95	6.1	0.58	700	0.04437	0.46	0.3189	0.76	0.05210	0.62	279.9	280.9	289.8	0.58
26	Pr melt incl	0.0048	4	380	18.05	2.2	0.57	2395	0.04465	0.35	0.3199	0.48	0.05194	0.19	281.6	281.8	282.6	0.94
27	Tip of brownish pr	0.0018	1	545	27.32	2.7	0.77	1059	0.04473	0.37	0.3213	0.67	0.05207	0.53	282.1	282.8	288.3	0.61
28	lpr euh	0.0025	3	379	18.63	5.3	0.69	522	0.04470	0.37	0.3217	0.85	0.05217	0.73	281.9	283.1	292.9	0.52
29	Frags of lpr	0.0010	3	878	42.08	1.7	0.62	1520	0.04448	0.47	0.3187	0.65	0.05197	0.50	280.5	280.9	284.0	0.64
Montorfano granite (SA-1)																		
30	Acic non abr	0.0070	4	475	21.42	11.1	0.37	869	0.04473	0.33	0.3207	0.56	0.05199	0.40	282.1	282.4	285.1	0.71
31	lpr	0.0036	1	389	18.01	18.0	0.40	242	0.04543	0.39	0.3292	1.44	0.05256	1.37	286.4	289.0	309.8	0.31
32	lpr	0.0057	1	239	11.97	34.6	0.67	132	0.04555	0.45	0.3380	2.68	0.05382	2.64	287.1	295.7	363.4	0.17

Table 1 continued

Number	Description[a]	Weight (mg)	No of grains	Concentrations				Atomic ratios							Apparent ages			Error corr.
				U	Pb rad. (ppm)	Pb nonrad. (pg)[b]	Th/U nonrad. (pg)[b]	206/204[c]	206/238[d]	Error 2σ (%)	207/235[d]	Error 2σ (%)	207/206[d]	Error 2σ (%)	206/238	207/235	207/206	
33	lpr euh	0.0015	1	629	24.80	9.2	0.30	276	0.03987	0.41	0.2862	1.31	0.05206	1.23	252.0	255.5	287.9	0.35
34	lpr euh	14.0000	1	571	24.95	1.0	0.25	2359	0.04484	0.39	0.3221	0.54	0.05100	0.36	282.8	283.5	289.7	0.75

[a] *abr* Abraded; *ac* acicular; *nonabr* nonabraded; *euh* euhedral; *clrls* colourless; *incl* inclusions; *pr* prisms; *frags* fragments; *spr* short prismatic; *subh* subhedral; P-type zircons after Pupin (1980)

[b] Calculated on the basis of radiogenic Pb^{208}/Pb^{206} ratios, assuming concordancy

[c] Corrected for fractionation and spike

[d] Corrected for fractionation, spike, blank and common lead (Stacey and Kramers 1975)

275 Ma, should include the majority of volcanic products of the AG. This interval agrees well with age results for nearby plutonic rocks including the 275.5 ± 1.5 Ma U–Pb allanite age for a member of the Cima d'Asta intrusives (Barth et al. 1994), as well as the older values of numerous but presumably less reliable Rb–Sr and K–Ar ages (e.g. Brixen: 281 Ma, Rb–Sr whole rock, Del Moro and Visonà 1982; Astjoch: 275.8 ± 2.5 Ma, Rb–Sr bio, 276 K–Ar bio, Stöckhert et al. 1990; Cima d'Asta: 275 ± 9, 274 ± 9 Ma, Rb–Sr whole rock, Borsi et al. 1974). However, this time span (285–275 Ma) does not confirm the older Ar–Ar biotite ages of 297.5 ± 3.3 and 285.7 ± 3.2 Ma reported by Hess (1990) for two volcanic layers of the northern AG.

Lugano-Valganna complex and "Laghi Granites"

Lower ignimbrite SU-98-4a (Ganna-Boarezzo, Valganna; Fig. 2d)

This sample included a variety of zircons of different colour, shape and age. Despite this diversity the U concentrations remain in a very narrow band of ca. 200–400 ppm. The U–Pb analyses revealed the presence of inherited components of different age leading to strongly discordant points with $^{207}Pb/^{206}Pb$ ages (i.e. minimum ages) of 1.6 Ga (analysis 22), 550 Ma (21) and 400 Ma (23). The remaining five analyses (17–20 and 24) yielded analytically concordant points at $^{206}Pb/^{238}U$ ages between 298 and 288 Ma. Possibly, this age approximately marks the emplacement of the basal ignimbrite within this caldera. Given the narrow range of ages of the whole study, and the older inherited grains in this sample, we interpret these ages as inherited from juvenile (late Variscan) orogenic crust.

Ganna Granite SU-98-3 (Boarezzo, Valganna; Fig. 2e)

The analysis of five microfractions of prismatic zircons consisting of 1–5 grains each, yielded concordant points scattering along the concordia at $^{206}Pb/^{238}U$ ages between 282.1 and 279.9 Ma. The position of the data suggests that inheritance and lead loss may bias the ages to some subordinate extent, which cannot be resolved. A concordant age of all five points of 281.3 ± 0.5 Ma is considered as the age of emplacement. An εHf value of +0.6 ± 0.8 has been reported for a bulk zircon fraction by Stille and Steiger (1991).

Montorfano Granite SA-1 (Fig. 2f)

The zircons of this sample are longprismatic to acicular and usually have S-type morphology with (211) bipyr-

Table 2 Hf isotopic analyses of dated zircons

Analysis[a]	$^{176}Hf/^{177}Hf$[b]	±2s	$^{176}Hf/^{177}Hf$ (T)	εHf (0)[c]	εHf (T)	±2σ[d]	T_{DM} (Ga)
Rhyodacite, Malga Baessa, Val Calamento (SU-99-7)							
4	0.282449	0.000003	0.282441	–11.4	–5.3	0.5	1.5
5	0.282462	0.000004	0.282454	–11.0	–4.9	0.5	1.5
6	0.282446	0.000005	0.282438	–11.5	–5.4	0.5	1.5
7	0.282423	0.000005	0.282415	–12.3	–6.2	0.5	1.6
Rhyolite, Albiano (SU-99-8)							
9	0.282522	0.000007	0.282514	–8.8	–2.8	0.5	1.4
10	0.282409	0.000007	0.282401	–12.8	–6.8	0.5	1.6
11	0.282526	0.000006	0.282518	–8.7	–2.6	0.5	1.3
Ignimbritic rhyolite, San Lugano (SU-99-6)							
13	0.282630	0.000016	0.282622	–5.0	+1.0	0.9	1.1
14	0.282628	0.000008	0.282620	–5.1	+0.9	0.6	1.1
15	0.282612	0.000007	0.282604	–5.7	+0.3	0.5	1.2
16	0.282603	0.000018	0.282595	–6.0	0.0	0.9	1.2
Montorfano granite (SA-1)							
30	0.282629	0.000016	0.282621	–5.1	+1.2	0.9	1.1
31	0.282512	0.000014	0.282504	–9.2	–3.0	0.8	1.4
32	0.282459	0.000016	0.282451	–11.1	–4.9	0.9	1.5
33	0.282439	0.000012	0.282436	–11.8	–5.6	0.7	1.5
34	0.282406	0.000011	0.282403	–12.9	–6.8	0.7	1.6

[a] Same numbers as in Table 1

[b] Measured values, corrected for fractionation and adjusted to JMC475 value of $^{176}Hf/^{177}Hf = 0.282460$

[c] εHf values were calculated with $(^{176}Hf/^{177}Hf)_{CHUR(0)} = 0.282772$ (Blichert-Toft and Albarède 1997)

[d] External reproducibility (±0.5 ε units) if individual run error <0.5 ε units

amid faces. Four very thin needles (unabraded, analysis 30) provided the only concordant analysis, indicating an emplacement age of 282 ± 1 Ma for this granite. A best-fit line through four analytical points (30, 31, 33 and 34) yields a lower intercept age interpreted as best estimate for the emplacement at 281.8 ± 1.5 Ma and an upper intercept age of an inherited Pb component of approximately 1.6 Ga. The emplacement age compares well with a published Rb–Sr whole-rock age of 277 ± 8 Ma (Pinarelli et al. 1988). The analysed zircons contain high levels of initial common lead. Three zircon fractions were analysed for initial Hf isotopic composition (Table 2). The concordant analysis 30 yielded an εHf of +1.2, whereas analyses 31 and 34 have strongly negative εHf values (–3.3 to –6.8). These compare perfectly with a value of –3.3 ± 1.3 for a bulk zircon fraction analysed by Stille and Steiger (1991). The zircon Hf isotope determinations yielded depleted mantle model ages of 1.4–1.5 Ga that agree with the $^{207}Pb/^{206}Pb$ age values.

Discussion

The well-defined ages of the Ganna granite (281.3 ± 0.5 Ma) and of the Montorfano granite (281.8 ± 1.5 Ma) are in agreement with the less precise whole-rock and mineral Rb–Sr isochron ages of Pinarelli et al. (1988) and Bakos et al. (1990). They do not support the interpretation by Stille and Buletti (1987), who considered a 262 Ma Rb–Sr mineral isochron age as dating the emplacement of the Lugano volcanics.

Age of near surface Permian magmatism, tectonism and sedimentation

The existing and new U–Pb age data from the upper crustal magmatic rocks are in good agreement and document magmatic activity in the South Alpine upper crust over a short time span of ca. 10 m.y., i.e. between 285 and 275 Ma (see compilation in Fig. 3). This figure also shows that there is no clear spatial age trend over a distance of >200 km, from east (AG) to west (Lugano/Valganna and Laghi granites) indicated by these results. In particular, there is also no firm evidence yet for the existence of magmatic products significantly older than 285 Ma. This is surprising in view of the ca. 300 Ma age assumed for the regional granulite facies metamorphism in the Ivrea-Verbano Zone (e.g. Vavra et al. 1996, 1999) and which is supposed by some authors to have produced substantial amounts of granitoid melts (e.g. Schmid and Wood 1976; Schnetger 1994).

The thick piles of volcanic rocks of the main districts of magmatism may, at least in part, represent the fills of large calderas, whereas the asymmetry of the continental Collio-type basins suggests a control by syndepositional tectonics (e.g. Cadel et al. 1996). Provided

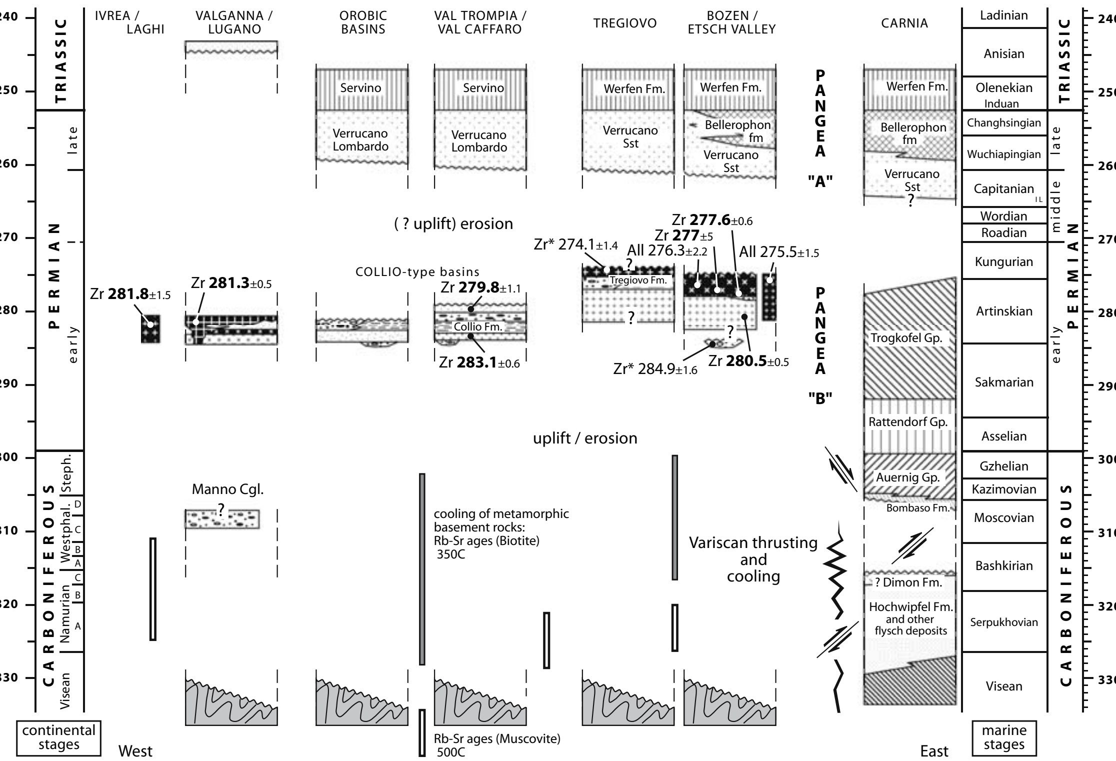

Fig. 3 Time scheme of Early Carboniferous to Permian marine and continental units of the Southern Alps with indicated reliable geochronologic information from upper crustal intrusives and volcanic rocks [U–Pb ages on zircons (this study) and allanite (Barth et al. 1994); Zr* indicate the oldest and youngest ages of AG in Klötzli et al (2003) and Marocchi et al. (2005)]. The numerical time-scale is adapted from Gradstein et al. (2004) with the exception for the ages of the base of the Changsingian (Mundil et al. 2004) and Triassic stages (Brack et al. 2005). Cooling ages mainly after data compiled in Martin et al. (1996) and Dal Piaz and Martin (1998)

the ca. 280 Ma age of ignimbrites in the Orobic basin (Philippe et al. 1987) is reliable, these basins likely formed contemporaneously. The age for the basal volcanics of the Val Trompia-Val Caffaro basin is close to the presumed age of the onset of the AG magmatic activity. Due to the erosive top of the volcano-sedimentary successions, the end of basin formation can nowhere be clearly established. Nevertheless, in agreement with paleontological evidence (Cassinis and Ronchi 2001), the sediments of the Tregiovo Fm. seem to post-date the presently visible sediment fills of the Collio-type basins. The erosional top marks a 15 m.y. sedimentary gap, since the overlying Verrucano/Val Gardena red beds are of Late Permian age (Fig. 3).

Crustal scale magmatism: age, genetic links and origin

The age of the ‘‘Mafic Formation’’ of the Ivrea-Verbano Zone is constrained by a ID-TIMS U–Pb zircon age of 285+7/–5 Ma of a diorite in its upper part (Pin 1986). Quick et al. (2003) report U–Pb ion-probe (SHRIMP) ages for an amphibolite gabbro (285 ± 4 Ma), a gabbro (287 ± 3 Ma) and a norite (287 ± 2 Ma). The authors identified the existence of mixed age populations in one of their samples (RA616), pointing to the presence of older age components. These SHRIMP ages, however, do not contradict the slightly older Pb–Pb evaporation ages of Garuti et al. (2001) between 287 and 292 Ma. The mixed population including Variscan (300 Ma-old) growth zones, however, urges for caution with the interpretation of these older ages, since the Pb–Pb ages are not able to resolve lead loss and inheritance. This leads to the conclusion that the deep crustal magmatism in the Ivrea-Verbano Zone is indeed broadly contemporaneous or may be only slightly older than the upper crustal and superficial magmatism of the ‘‘Laghi Granites’’ and the volcanic rocks adjacent to Lago Maggiore, as already proposed by a number of authors.

Comparable age values of gabbroic to dioritic complexes in the Austroalpine domain include the Braccia-Fedoz gabbro (281 ± 19 Ma) and a related leucogranite (278–2.5/+2.6 Ma) both from Hansmann et al. (2001), the Sondalo gabbroic complex (280 ± 10 Ma, Sm–Nd, Tributio et al. 1999), the gabbro of Anzasca (288+2/–4 Ma, U–Pb zircon, Bussy et al. 1998, erroneously called Sermenza gabbro) and the gabbro complex of Mt. Collon (284.2 ± 0.6 and 282.9 ± 0.6 Ma, U–Pb zircon, Monjoie et al. 2001, 2007; Monjoie 2004) and suggest that crustal-scale magmatism involving melts from mantle and crust sources was obviously a widespread phenomenon in the Early Permian in both the Austroalpine and South Alpine domains.

Among the Permian upper crustal intrusive rocks, the gabbroic–noritic ''appinites'' from the border area between the Ivrea-Verbano Zone and the ''Serie dei Laghi'' are considered as the melts with least contamination by crustal materials (Pinarelli et al. 2002). Petrographical, geochemical and isotopic data of the ''Laghi Granites'' (e.g. Boriani et al. 1988, 1995) exhibit a metaluminous character of a medium-K calc–alkaline series (Pinarelli et al. 2002) and indicate the hybrid nature of the melts. Participation of mantle melts in the generation of the intermediate and acid intrusions is inferred from Nd, Sr and Pb isotopic compositions (Pinarelli et al. 1993, 2002; Rottura et al. 1998). The magmas have been considered as products of combined assimilation and fractional crystallisation (AFC) of mantle derived liquids residing at the base of the crust (Stille and Buletti 1987; Mulch et al. 2002; Pinarelli et al. 2002), or of MASH-type hybridisation processes (Barth et al. 1993; Rottura et al. 1998; Voshage et al. 1990). These interpretations consistently point to the significant contribution of mantle-derived melts in the formation of a large proportion of the Early Permian magmatic rocks of the Southern Alps. An origin from exclusively crustal sources through the extraction of melt during granulite facies metamorphism (Schmid and Wood 1976; Schnetger 1994) therefore seems unlikely, even for the granitoid magmas as discussed previously by Zingg et al. (1990).

The parental liquids of the Permian magmatic rocks were suggested to be MOR-type basalt by Voshage et al. (1990), or alternatively considered to be derived from geochemically and isotopically enriched lithospheric mantle (Rottura et al. 1998), or from mantle that has been metasomatised during Paleozoic subduction (Pinarelli et al. 2002). The Permian gabbroic rocks in the Austroalpine units are thought to have evolved from tholeiitic parental liquids generated through decompression of upwelling spinel peridotites during lithospheric thinning (e.g. Tribuzio et al. 1999; Hermann et al. 2001; Montanini and Tribuzio 2001). Many models infer an enriched subcontinental mantle yielding the parental melts representing the mantle endmember. On the other hand, the mafic rocks that were thought to represent these parental melts turned out to be contaminated by crust. The most elevated εHf value for a mafic rock is reported for a gabbro from the Ivrea-Verbano Zone (Stille and Steiger 1991) and is not higher than εHf = +1.4 ± 0.9. The analyses of initial Hf isotopes of zircons dated in this study (Table 2) again suggest such mixing of mantle and crustal components, but do not give more precise information on the nature of possible endmembers.

Table 3 Compilation of Sr and Nd isotopic data from mafic rocks of the South-Alpine realm

Area	Lithology	$^{87}Sr/^{86}Sr$ (285 Ma)	$^{143}Nd/^{144}Nd$ (285 Ma)	εNd (285 Ma)	Data source
Serie dei Laghi	Appinite	0.705100	0.512270	–0.06	Pinarelli et al. (2002)
	Appinite	0.704400	0.512220	–1.03	Pinarelli et al. (2002)
	Appinite	0.707200	0.512150	–2.40	Pinarelli et al. (2002)
Sondalo	Gabbro	0.703700	0.512480	4.04	Tribuzio et al. (1999)
	Gabbro	0.705700	0.512150	–2.40	Tribuzio et al. (1999)
Internal Ligurides	Peridotite	0.702215	0.512597	6.32	Rampone et al. (1998)
	Peridotite	0.702217	0.512627	6.92	Rampone et al. (1998)
	Peridotite	0.702233	0.512692	8.18	Rampone et al. (1998)
	Peridotite	0.702295	0.512751	9.33	Rampone et al. (1998)
	Peridotite	0.702203	0.512717	8.67	Rampone et al. (1998)
Platta	cpx from peridotite	n.d.	0.512714	8.61	Müntener et al. (2004)
	cpx from peridotite	n.d.	0.512743	9.17	Müntener et al. (2004)
Ivrea	Baldissero peridotite	0.704047	0.512687	8.09	Voshage et al. (1990)
	Balmuccia peridotite	0.706300	0.512409	2.65	Voshage et al. (1990)
	Peridotite	0.704156	0.512385	2.19	Voshage et al. (1990)
	Pyroxenite	0.703458	0.512408	2.64	Voshage et al. (1990)
	Gabbro	0.704196	0.512559	5.60	Voshage et al. (1990)
	Gabbro	0.704634	0.512425	2.96	Voshage et al. (1990)
	Pyroxenite	0.703518	0.512383	2.15	Voshage et al. (1990)
Mt Collon	Mafic dyke	0.702910	0.512639	7.14	Monjoie(2004)

n.d. Not determined

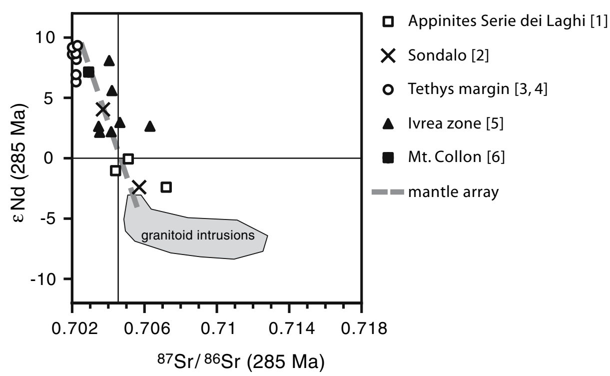

Fig. 4 εNd versus $^{87}Sr/^{86}Sr$ isotopic ratios of Permian mafic and acid magmatic rocks from the South-Alpine and Austroalpine domains. Source of the data: [*1*] Pinarelli et al. (2002); [*2*] Tribuzio et al. (1999); [*3*] Rampone et al. (1998); [*4*] Müntener et al. (2004); [*5*] Voshage et al. (1990); [*6*] Monjoie (2004)

A selection of published Nd and Sr isotopic data of Permian igneous rocks is compiled in Table 3 and Fig. 4. Two types of mantle could have been involved in magma generation: depleted asthenospheric MORB-type mantle and a geochemically enriched subcontinental mantle. A geochemical estimate for the Central European Continental Mantle (“CEEM”; Stille and Schaltegger 1996) suggests an age of ca 1.0 Ga for its separation from the convecting asthenosphere as a time-integrated steady-state reservoir with a mean Sm/Nd ratio of 0.168. For Variscan times this mantle would yield an εNd value of around +5 to +7, thus corroborating Pinarelli et al.’s (2002) estimate for the mantle pole of their AFC calculations. However, the highest εNd values obtained on rocks of the Ivrea and Mt. Collon gabbros range up to +9 (Fig. 4) and are thus close to a mantle endmember that is more depleted than the “CEEM” of Stille and Schaltegger (1996).

Jurassic extension and continental breakup has exhumed and exposed the subcontinental mantle of the Adriatic passive continental margin in different areas, e.g. in the Ligurides and in the South-Pennine Platta nappe (e.g. Marroni et al. 2001; Desmurs et al. 2001). The recorded εHf and εNd values of basalts and gabbros are typical for a depleted mantle composition (see Fig. 4; Rampone et al. 1998; Schaltegger et al. 2002; Müntener et al. 2004) and demonstrate that the Variscan crust was, at least in part, underlain by depleted mantle and that the mantle endmember estimates of, e.g. Pinarelli et al. (2002) may already represent crust-mantle mixtures. We therefore assume that partial melts from a depleted mantle were contaminated by crustal melts, produced through the advection of heat released from intruding mafic melts. Contact melting around intrusions of the “Mafic Formation” in the Ivrea-Verbano Zone was described by Zingg (1980), Bürgi and Klötzli (1990), Barboza et al. (1999) and Barboza and Bergantz (2000). The mixing of mantle and crustal sources is recorded by a single zircon population from the Montorfano granite where εHf values between +1.2 and –6.8 vary together with the degree of Proterozoic inheritance.

The initial Hf isotopic ratios from different volcanic lithologies of the southern part of the Athesian Volcanic Group (Table 3) show an increase of the εHf with decreasing age, i.e. from values of –6 (dacite SU-99-7) at 281 Ma to +1 (rhyolite SU-99-6) at 278 Ma. This means that over a few millions of years the mantle proportion in the melts was increasing. The most evolved rhyolites at the top of the sequence near San Lugano and Albiano (samples SU-99-6 and SU-99-8) are isotopically more primitive than the dacites close to the base of the volcanic succession of Val Calamento (Figs. 2, 5a, b). This relationship could be explained by crustal thinning and melting of uprising mantle in an extensional tectonic setting.

Geodynamic context of Permian magmatism

Based on the assumed genetic relationships between intrusive rocks of the lower crustal Ivrea-Verbano Zone and the adjacent upper crust of the Laghi area, several models have been proposed for the emplacement of mafic magmas (e.g. Rutter et al. 1993; Quick et al. 1994) as well as for the entire crustal-scale magmatism (e.g. Handy and Zingg 1991; Sinigoi et al. 1994; Handy et al. 1999; Snoke et al. 1999), despite the poor geochronological database. Melt ascent was proposed to occur through a network of granite sheets (Snoke et al. 1999) or through conduits primarily along crust-scale transtensional, oblique-slip faults (Handy and Streit 1999; Mulch et al. 2002). Where such faults emerge at the surface they are thought to have controlled the formation of volcano-sedimentary basins. Common to all these models is an inferred extensional component of the tectonic regime for Permian magmatism and associated high-temperature shearing in the lower crust. The proposed close temporal relationship between magmatic rocks at all levels of the crust is indeed supported by the narrow range (285–275 Ma) of precise ages from upper crustal magmatic rocks as discussed previously.

A synthetic transect of one of the best examples of a crustal cross sections in the Ivrea-Verbano Zone to Laghi area is provided by Rutter et al. (1999) and largely corresponds to the present geological map put upright and with a flattened base close to the level cut

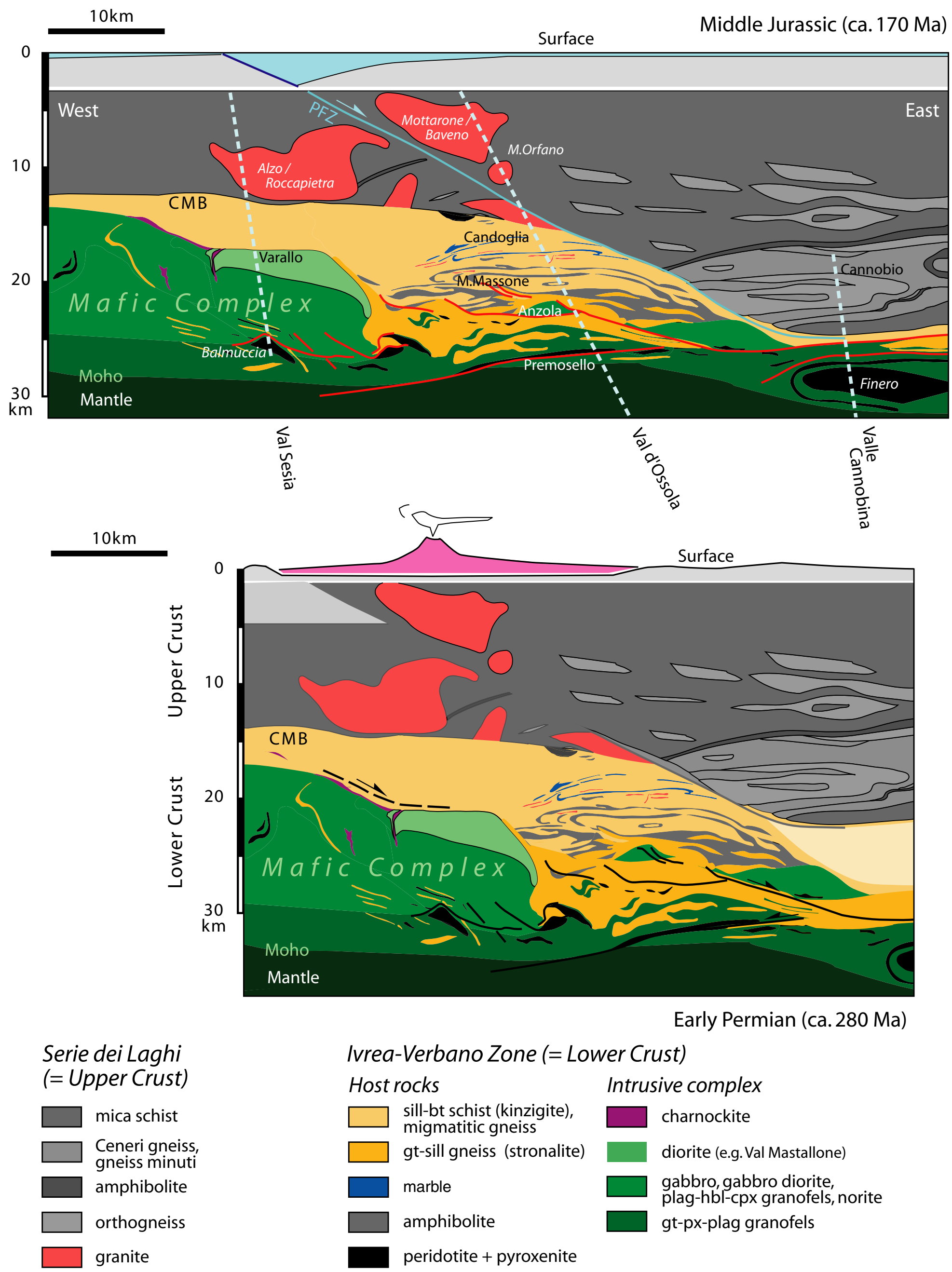

Fig. 5 Tentative schematic reconstruction of Permian crust of the Ivrea-Verbano Zone—Laghi area obtained by retrodeformation of a simplified (reflected) version of the restored cross section in Rutter et al. (1999, 2003). See Fig. 6 for the removal of pre-Alpine deformation

by the Insubric fault (for details of reconstruction see Rutter et al. 1999, 2003). This crust section depicts the situation prior to the Alpine uplift and does not account for earlier deformation. To arrive at the Early Permian situation, we removed the Triassic–Jurassic displacement along the Pogallo Line (around 11 km, see Handy 1987) and the Permian high-T deformation (e.g. Rutter et al. 1993, Snoke et al. 1999) starting from a simplified version of the Rutter et al. (1999) section, shown in Fig. 5. The main steps of this retrodeformation are highlighted in Fig. 6. For the Early Permian reconstruction the depth level of the lower crust falls within the range of pressures established for the Ivrea-Verbano Zone.

We consider the proposed crustal section to be representative for large parts of the central and western Southern Alps. A summary section through the Early Permian crust along the entire Southern Alps and with representative age information is shown in Fig. 7. For the upper crustal part the estimated post-Permian Mesozoic extension has been removed on major fault zones: the Lago Maggiore fault, the Lugano fault and the border faults limiting the Mesozoic Trento platform (Bertotti et al. 1993). The cross-sec-

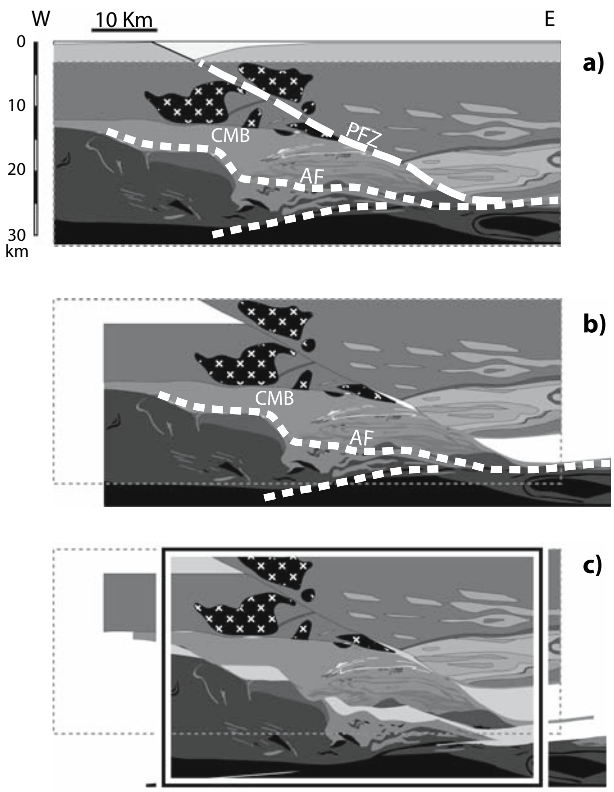

Fig. 6 Reconstruction of Permian crust as displayed in Fig. 5. **a–b** Removal of ca. 11 km of Jurassic fault displacement along the Pogallo Fault Zone (PFZ). **b–c** Removal of (supposedly Permian) 110% pure shear ductile extension of lower crust beneath the CMB-Line as well as along high-T fault zones [Rutter et al. 1993; Snoke et al. 1999; assumed slip component: ca. 5.5 km on the Anzola Fault Zone (AF) and 2.5 km on a structurally deeper fault zone]

tion displays troughs filled with marine sediments (Carnia), intracontinental basins dominated by volcanic and clastic rocks, intrusions in the upper and middle crust and magmatic rocks emplaced close to the base of the crust, which all correspond to the time window of 285–275 Ma (Fig. 3).

Evidently, the whole area along the South Alpine cross-section was affected by Early Permian extensional tectonic activity. It is usually attributed to either a phase of post-collisional collapse of the Variscan orogen (e.g. Henk et al. 1997) or to strike-slip movements along the southern border of this mountain chain (e.g. Handy and Zingg 1991). However, recent paleomagnetic data on precisely dated magmatic rocks led Muttoni et al. (2003) to revive the possibility of a large scale transformation of the supercontinent Pangea as initially envisaged by Irving (1977). In order to eliminate continental overlap and crustal misfit between Gondwana and Laurasia and as a result of a reconstruction based on Early Permian mean paleopoles, Muttoni et al. (2003) propose a >2,000 km dextral megashear between Gondwana and Laurussia, which may have transformed Pangea from an Early Permian ‘‘B’’ to a Late Permian ‘‘A’’ configuration. Lithosphere-scale extension with melt generation in the mantle could result in all of the above mentioned scenarios. However, the short duration and the abrupt apparent end of magmatic activity along with the gap in the sedimentary record of the Southern Alps (Fig. 3) are compatible with the model proposed by Muttoni et al. (2003). In this scenario, the crustal-scale extension and magmatism observed in the Southern Alps and adjacent areas would represent the initial transtensional phase of this continental reorganisation.

Conclusions

The following main points emerge from the dating of Lower Permian rocks and the reconstruction of the unique coherent Early Permian crustal sections of the Southern Alps:

1. Precise U–Pb-age data constrain the main period of Early Permian magmatic activity in the South Alpine upper crust to a narrow interval between 285–275 Ma. This time span also includes the formation of small asymmetric continental basins of tectonic and partly of possible volcanic origin. With respect to Variscan deformation and metamorphism this interval is clearly post-orogenic and there is probably no causal relationship between the two.
2. The lack of dated magmatic rocks with isotopic ages significantly older than 285 Ma suggests that the granulite-facies metamorphism in the deep crustal portions either did not produce significant amounts of granitic melt to reach shallow levels or that the published data from granulite-facies rocks around 290–300 Ma do not reflect the main magma-forming stage of the granulite–metamorphic overprint.
3. Available age data from the deep-seated mafic intrusives of the Ivrea-Verbano Zone suggest that they are roughly coeval with the oldest dated granitoid rocks that occur at shallow levels. Additional data from the Austroalpine units confirm the widespread occurrence of basic magmatism in the middle to lower crust. During subsequent Mesozoic break-up and continental separation, this zone became the northwestern border zone of the Adriatic microplate.

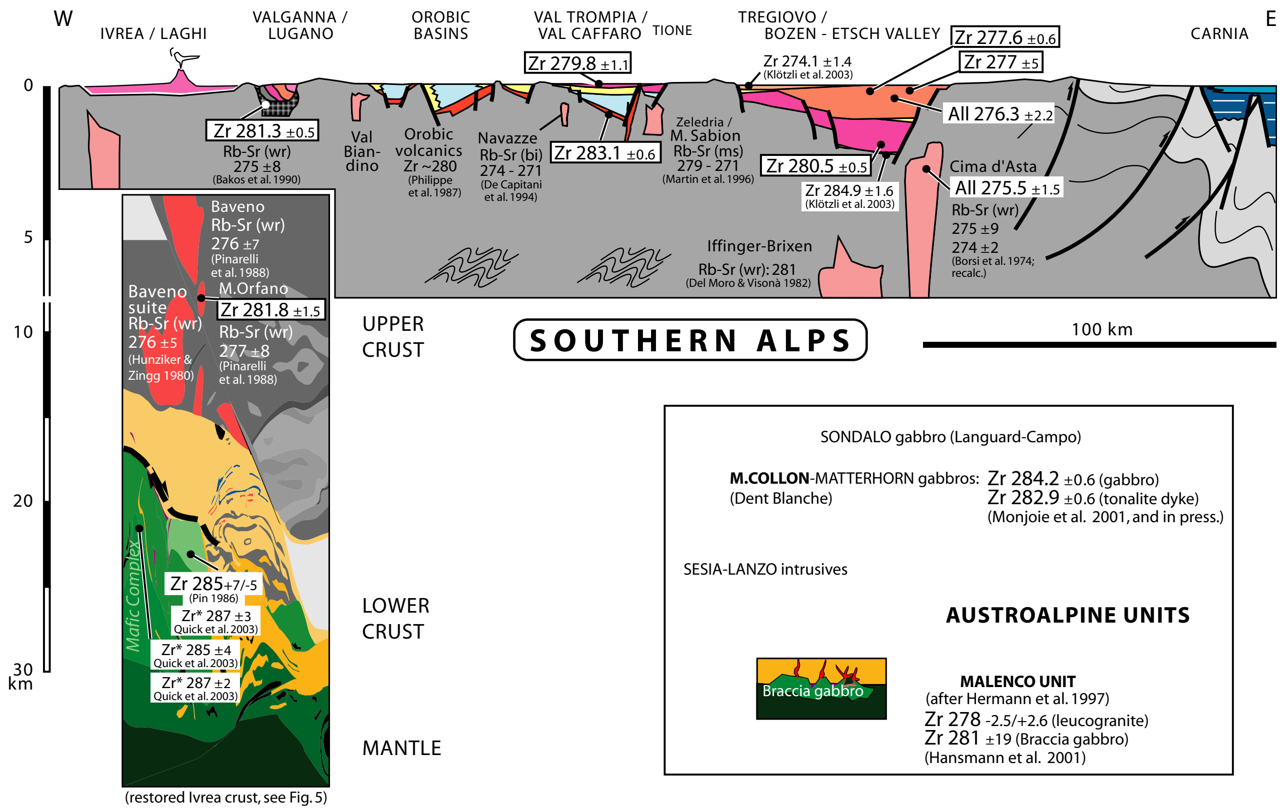

Fig. 7 Schematic synthetic E–W cross section of the Early Permian crust of the Southern Alps (see Fig. 1) with U–Pb-age results (*Zr*: zircon, this study were not otherwise indicated; *All*: allanite from Barth et al. 1994) and selected Rb–Sr-age data of Early Permian magmatic rocks. Mesozoic extension on major fault zones (Lago Maggiore Fault, Lugano Fault, border areas of Trento platform) has been removed. Colour code of Ivrea-Laghi crust section as in Fig. 5; undifferentiated upper crustal metamorphic basement (*grey area*) and little to non-metamorphic pre-Moscovian successions of Carnia (*light grey*) are indicated schematically. *Red colours* mark plutonic and volcanic rocks; non-volcanic sedimentary basin fills comprise mainly fluvio-lacustrine clastic rocks (*light blue*) coarse alluvial deposits (*yellow*) and in Carnia, marine carbonates and clastics (*dark blue*). Note change of vertical scale corresponding to ca. 7 km depth-level. Complementary age information from Austroalpine units is shown in the *inset*; pressure at petrologic crust/mantle boundary of Malenco Unit at the time of intrusion of Braccia Gabbro is constrained by metamorphic and magmatic mineral assemblages to around 1.0 GPa (Hermann et al. 2001)

4. The isotopic compositions of Lower Permian magmatic rocks at all crustal levels point to a mantle source for the parental magmas which, during their ascent through the crust, were contaminated to variable degrees by crustal rocks.
5. Lower Permian magmatic products and structural features of the Southern Alps seem to be linked to a phase of crustal-scale extension. The short duration of magmatism and the subsequent hiatus in sediment deposition are compatible with the generation of magma during the initial transtensive phase of continental-scale strike-slip.

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